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Literature Survey on Operator Performance using Multiple Displays

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Contract Number: W7707-05-2970

Contract Scientific Authority: Dr. Jacquelyn Crebolder, 902-426-3100 ext 296

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2005-209
March 2006

Canada

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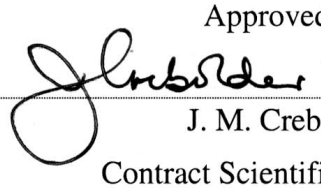

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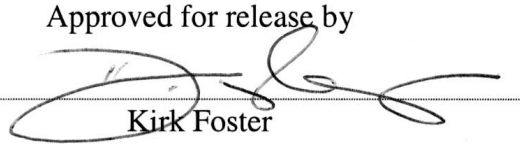

Kirk Foster

DRP Chair

Abstract

A survey has been completed to investigate literature in the area of operator performance using multiple displays, in order to support a variety of projects in the Maritime Command, Control, Communications, Computer and Intelligence (C4I) environment at Defence Research and Development Canada (DRDC) – Atlantic. Using a defined set of keywords and literature sources, various documents, reports, papers and articles were found, of which 100 were assessed according to a set of criteria that identified those that were more useful for adaptation to the present project's goals and objectives. Of the literature identified in the survey, 7 were reviewed in detail and summarized.

Résumé

Une étude des documents portant sur le rendement des opérateurs qui travaillent avec des affichages multiples a été menée dans le but d'appuyer une variété de projets de commandement, de contrôle, de communications, d'informatique et de renseignement (C3IR) dans le milieu maritime à Recherche et développement pour la défense Canada - Atlantique (RDDC). À l'aide d'un ensemble défini de mots clés et de sources documentaires, nous avons trouvé divers documents, rapports, journaux et articles. Nous avons évalué 100 de ces documents en fonction d'un ensemble de critères qui ont permis de cerner ceux qui s'adapteraient le mieux aux objectifs et aux buts du projet en cours. À partir des documents retenus, nous en avons examiné 7 en détail et les avons résumés.

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Executive summary

Literature survey of operator performance using multiple displays

Delle Donne, V.; DRDC Atlantic CR 2005-209; Defence R&D Canada – Atlantic, March 2006.

Introduction or background

This document is the final report of a project to investigate literature in the area of operator performance using multiple displays, in order to support a variety of projects in the Maritime Command, Control, Communications, Computer and Intelligence (C4I) environment. The report has been prepared by Valcom Consulting Group Inc. for the Defence Research and Development Canada (DRDC) – Atlantic under Public Works and Government Services Canada (PWGSC) Contract No. W7707-05-2970.

Results

Using a defined set of keywords and literature sources, various documents, reports, papers and articles were found, of which 100 were assessed according to a set of criteria that identified those that were more useful for adaptation to the present project's goals and objectives. Of the literature identified in the survey, 7 were reviewed in detail and summarized.

The type of literature identified indicated that there is more relevant literature in the military than the maritime domain. There is also a substantial base of literature from basic research, which is directed mostly at visual displays. This literature base, however, does not have much depth. Much of the literature is at the experimental phase of development. This reflects the lack of maturity of the domain, in that fewer new ideas have been generated than have been tested.

In cases where actual evaluations of multiple display technologies have been conducted there are a number of concerns with the quality of research, particularly as a result of unrepresentative subject groups and tasks, inappropriate measures, and poor interface design of displays.

Military significance

A serious challenge for operational C4I systems is how operators deal with extensive amounts of information and, accordingly, the complexity of operator-machine interface displays. It is anticipated that the C4I system operator of the future will perform multiple tasks and monitor and attend to several displays concurrently. Understanding the issues related to human

performance using multiple displays is key to providing appropriate and effective tools and systems to best support tasks of the user in the military environment.

Future plans

To address weaknesses in the literature and develop guidance for future operator performance using multiple displays in the maritime environment, it is recommended that a research and development program be conducted, as follows:

1. Extend the literature review on operator performance using multiple displays;
2. Conduct maritime multiple display experiments; and
3. Coordinate and consolidate multiple display research.

Sommaire

Étude documentaire sur le rendement des opérateurs travaillant avec des affichages multiples

Delle Donne, V.; DRDC Atlantic CR 2005-209; R & D pour la défense Canada – Atlantique; March 2006.

Introduction ou contexte

Le présent document constitue le rapport final du projet visant à examiner les documents portant sur le rendement des opérateurs qui travaillent avec des affichages multiples dans le but d'appuyer une variété de projets de commandement, de contrôle, de communications, d'informatique et de renseignement (C3IR) dans le milieu maritime. Le rapport a été préparé par Valcom Consulting Group Inc. pour Recherche et développement pour la défense Canada – Atlantique (RDDC) dans le cadre du contrat n^{o} W7707-05-2970 avec Travaux publics et Services gouvernementaux Canada (TPSGC).

Résultats

À l'aide d'un ensemble défini de mots clés et de sources documentaires, nous avons trouvé divers documents, rapports, journaux et articles. Nous avons évalué 100 de ces documents en fonction d'un ensemble de critères qui ont permis de cerner ceux qui s'adapteraient le mieux aux objectifs et aux buts du projet en cours. À partir des documents retenus, nous en avons examiné 7 en détail et les avons résumés.

De plus, le type de documents recensés a indiqué qu'il y a davantage de documents pertinents dans le domaine militaire que dans le domaine maritime. Il existe aussi un nombre important de documents créés à partir de recherches fondamentales, et dont le sujet porte généralement sur les affichages multiples; toutefois, ce sujet n'y est pas vraiment traité en profondeur. La majorité de ces documents traitent de points à l'étape expérimentale de leur développement, ce qui illustre le manque de maturité du domaine (c.-à-d. que le nombre de nouvelles idées générées est inférieur au nombre de nouvelles idées testées).

Dans les cas où de réelles évaluations de la technologie des affichages multiples ont été effectuées, la qualité de la recherche suscite bon nombre d'inquiétudes en raison, plus particulièrement, des groupes et des tâches peu représentatifs, des mesures inappropriées ainsi que de la conception déficiente de l'interface des affichages.

Importance militaire

La manière dont les opérateurs traitent les énormes quantités d'informations et, par conséquent, la complexité des affichages de l'interface opérateur-machine représente un grave défi pour les systèmes C4I. Il est prévu que l'opérateur des systèmes C4I de l'avenir assumera des tâches multiples et surveillera et s'occupera de plusieurs affichages en même temps. Il est essentiel de comprendre les problèmes liés à la performance humaine où il est question de multiples affichages si on veut offrir des outils et des systèmes appropriés et efficaces pour mieux soutenir les tâches de l'utilisateur dans l'environnement militaire.

Perspectives

Afin de s'attaquer aux lacunes entourant les documents et de développer une directive pour le rendement des futurs opérateurs travaillant avec des affichages multiples dans le milieu maritime, nous recommandons qu'un programme de recherche et de développement soit mis en place en fonction des paramètres suivants :

1. Élargir l'examen des documents sur le rendement des opérateurs qui travaillent avec des affichages multiples.

2. Effectuer des expériences connexes aux affichages multiples dans le domaine maritime.

3. Coordonner et regrouper les recherches sur les affichages multiples.

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1. Introduction

This document is the final report of a project to investigate literature in the area of operator performance using multiple displays, in order to support a variety of projects in the Maritime Command, Control, Communications, Computer and Intelligence (C4I) environment. The report has been prepared by Valcom Consulting Group Inc. for Defence Research and Development Canada (DRDC) – Atlantic under Public Works and Government Services Canada (PWGSC) Contract No. W7707-05-2970.

1.1 Background

A serious challenge for operational C4I systems is how operators deal with extensive amounts of information available to them and, accordingly, the complexity of operator-machine interface displays. As technology produces more advanced sensors, and the ability to extract and distribute data becomes more efficient and achievable, the quantity of information delivered to an operator will continue to increase. It is anticipated that the C4I systems operator of the future will perform multiple tasks and monitor and attend to several displays concurrently using systems that draw on visual, auditory, and haptic modalities.

Spatially distributing information across several displays extends the area to which the operator must attend. Research in human attention suggests that performance can suffer when attention must be deployed and maintained over a wide field of view. With future C4I systems in mind, interface design must provide easily accessible decision support to operators performing multiple tasks and monitoring and attending to multiple information sources.

A research program to investigate human performance using multiple displays in the context of Maritime C4I is being developed at DRDC Atlantic. The program will explore theoretical issues surrounding attentional limitations and operator workload using multiple displays in support of emerging and existing Maritime projects.

To support a variety of projects in the Maritime C4I environment DRDC Atlantic has requested an in-depth overview of research that has been conducted in the area of human performance using multiple displays.

1.2 Purpose

The overall intentions of the literature survey were to:

4. Review the open literature and collect knowledge from other practitioners in the area of human performance using multiple displays, including but not limited to attentional limitations, sustained attention, and workload; and

5. Obtain an appreciation of performance issues and areas for future research with respect to operator-machine interfaces in the Maritime C4I environment.

1.3 Scope

The scope of this project was established through the Statement of Work developed by the Scientific Authority, combined with limits placed on the literature that could be reviewed within the project budget.

The project was requested to be completed in the following steps:

A thorough search of the literature dealing with operator performance using multiple displays;

A critical analysis of the literature results and methodologies, assessing its strengths and limitations of existing research, and describing the data collection, analysis, and reporting techniques;

A determination of the current knowledge and problems of human performance when using multiple displays;

Identification of current strategies used by operators in various industries, as well as military; and

The formulation of conclusions and recommendations consistent with the goals of the survey.

In order to remain within the project budget it was determined that up to approximately 150 documents, reports, papers and/or articles would be entered into the project database, while approximately 7 would be reviewed in detail.

1.4 Deliverables

The deliverables required from this literature survey project included:

Annotated biography summarizing the breath and depth of the literature; and

Draft and final reports to further summarize and assess the relevance of the literature findings, and determine the future research and development activities that may be required.

2. Methodology

The literature survey was conducted through the methodology outlined in the following subsections.

2.1 Literature Survey and Preliminary Review

The project Statement of Work called for a survey to assess the breadth and depth of the immediately available literature related to human performance using multiple displays. This was to be followed with an assessment of the relevance of the literature to the use and design of Maritime C4I systems and provide recommendations for future research.

Activities included literature search and preliminary review in order to classify the type of literature and the level of research.

2.1.1 Strategy

The project began with the development of the literature search strategy, by defining multiple displays for the purpose of the project, defining operator performance impacts of multiple displays, identifying the key search terms required, and identifying the sources of literature that should be searched.

An iterative search strategy was used, such that literature sources would be searched in multiple passes, identify the most relevant literature on the first pass, and then return to obtain another level of literature. These iterations allowed the incremental identification of literature, prioritized by project objectives while at the same time remaining within the project scope.

2.1.2 Definitions

An operator-machine system can be considered as a combination of one or more operators and one or more physical components interacting to bring about from given inputs some desired out. The machine can consist of virtually any type of physical object, device, equipment, facility, thing, or what have you that operators use in carrying out some activity that is directed toward achieving some desired purpose or in performing some function. The essential nature of an operator's involvement in a system is an active one, interacting with the system to fulfill the function for which the system is designed. The typical type of interaction between an operator and a machine is illustrated in ***Figure 1*** (*Schematic Representation of an Operator-machine System*).

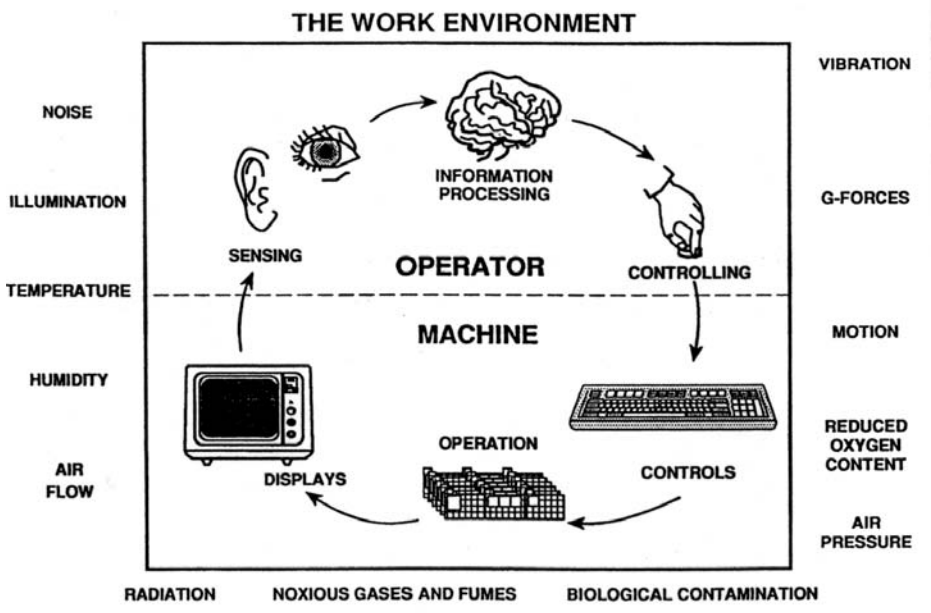

Figure 1. Schematic Representation of an Operator-machine System

This illustration shows how the displays of a machine serve as stimuli for an operator, trigger some type of information processing on the part of the operator (including decision making), which in turn results in some action that controls the operation of the machine.

In the present context, the term display refers to the presentation of information to any of the human senses, not necessarily just to the eyes. The purpose of the display in a system is to give information to the operator about the functional condition of the system or the process. The information can be categorized as follows: need to know, nice to know and historical.

Information is sometimes displayed in a confusing way, with less critical data obscuring the presence of information on which action must be taken. Because the purpose of a display is to notify the operator of a situation, two prime concerns are to make the signal easily detectable and to have it indicate clearly any required actions. There are several modes by which information from displays is conveyed to an operator: visual, auditory, and haptic (tactile).

Visual presentation is preferred for complex messages in noisy environments where response time is not critical. Auditory presentation is preferred for simple messages in areas where people move around frequently and where response time must be rapid. Usually auditory displays supplement visual presentation by drawing the operator's attention to the visual display that provides detail of the system. Auditory displays are particularly well suited to represent infrequently occurring information where it is necessary to gain the operator's attention. Haptic (tactile) modes are being employed

more often as people are bombarded with more information, especially when there is high ambient noise or vision is obscured.

Displays of a system can either facilitate interaction or increase task difficulty and the probability of error. The German *Gestalt* psychologists in the first half of the twentieth century described how the way stimuli are structured determines how they are perceived. The structure of a display is of superior importance to any particular element within it. Hence the *Gestalt* dictum "the whole is greater than the sum of its parts". Conscious perceptions result not just from an analysis of objects in the field of view (FOV) but from a synthesis of the objects themselves and the relation between them.

Finally, human performance measures are usually frequency measures (such as number of targets detected), latency measures (such as reaction time or delay in switching from one activity to another), duration measures (such as time on target in a tracking task) or reliability measures (such as probability of errorless performance). Sometimes combinations of these basic types are used, such as number of missed targets per unit time.

2.1.3 Keywords

As a result of the project planning activities and consultation with the scientific community, the following list of primary keywords were used in combination (i.e., multiple AND display) in the literature search:

Performance;

Operator performance;

Human performance;

Display; and

Multiple displays.

These keywords focused on the concept of multiple displays and some of the key human behaviour (such as human limitations and workload) that would underlie performance impacts of multiple display use.

Other keywords were used for basic research issues that likely relate to multiple display requirements, such as:

Visual display;

Auditory display;

Haptic (tactile) display;

Human-machine interface;

Human-computer Interaction;

Operator-machine interface;

Visual Search;

Perception;

Attention;

Vigilance;

Workload;

Change blindness;

Attentional blink;

Attentional limitations;

Sustained Attention;

Attentional spotlight; and

Field of view (FOV).

2.1.4 Databases

The literature search was conducted using various primary sources.

Firstly, literature was obtained by searching scientific literature databases (including PsycINFO, PsycARTICLES, and Compendex to name a few) accessed through the Champlain library at Université de Moncton in New Brunswick.

Then a considerable amount of literature search was conducted on-line, using Copernic desktop search engine. Within the scientific literature, a number of websites and databases were searched including:

Association of Canadian Ergonomists (ACE) (http://www.ace-ergocanada.ca)

Association of Computing Machinery (ACM) (http://www.acm.org)

Association of Computing Machinery (ACM) Portal Digital Library (http://portal.acm.org)

Atomic Energy of Canada Limited (AECL) (http://www.aecl.ca)

Australian Department of Defence, Defence Science and Technology Organization (DSTO) (http://www.dsto.defence.gov.au)

Cognitive Task Analysis (CTA) Resource (http://www.ctaresource.com)

Department of National Defence (DND), Defence Research and Development Canada (DRDC) (http://pubs.drdc-rddc.dnd.ca)

Edinburgh Engineering Virtual Library (EEVL) (http://www.eevl.ac.uk)

Electronic Power Research Institute (EPRI) (http://www.epri.com)

Engineering Information (http://www.ei.org)

Human-Computer Interaction (HCI) Bibliography (http://www.hcibib.org)

Human Factors and Ergonomics Society (HFES) (http://www.hfes.org)

IngentaConnect (http://www.ingentaconnect.com)

Lawrence Erlbaum Associates (LEA) Online (http://www.leaonline.com)

MetaPress (http://www.metapress.com)

National Aeronautics and Space Administration (NASA), Johnson Space Center, Man-Systems Integration Standards (MSIS) (http://msis.jsc.nasa.gov)

National Research Council Canada (NRC), Canada Institute for Scientific and Technical Information (CISTI) (http://cisti-icist.nrc-cnrc.gc.ca)

Pacific Science & Engineering Group (http://www.pacific-science.com)

QinetiQ (http://www.qinetiq.com)

U.S. Nuclear Regulatory Commission (NRC) (http://www.nrc.gov)

U.S. Department of Defense (DoD), Defense Technical Information Center (DTIC), Directory of Design Support Methods (DDSM) – MATRIS (http://www.dtic.mil/matris/ddsm/)

U.S. Department of Defense (DoD), Defense Technical Information Center (DTIC), Human Factors Engineering Technical Advisory Group – Standardization (http://hfetag.dtic.mil)

U.S. Department of Defense (DoD), Defense Technical Information Center (DTIC), Information Analysis Centers (IAC), Human Systems Information Analysis Center (HSIAC) (http://iac.dtic.mil/hsiac/)

U.S. Department of Defense (DoD), Space and Naval Warfare Systems Command (SPAWAR) (http://enterprise.spawar.navy.mil)

U.S. Department of Transportation (DoT), Research and Special Programs Administration (RSPA), John. A. Volpe National Transportation Systems Center, Operator Performance and Safety Division (OPSAD) (http://www.volpe.dot.gov/opsad/)

2.2 Literature Categorization and Ranking System

Once relevant titles were obtained they were further reviewed and categorized using a matrix illustrated in ***Table 1*** (*Literature Categorization Matrix*) below.

Table 1. Literature Categorization Matrix

		LITERATURE TYPE			
		CONCEPT	LAB	FIELD	REVIEW
DOMAIN RELEVANCE	MARITIME				
	MILITARY				
	INDUSTRY				
	BASIC				

The four categories of ***Domain Relevance***, from lowest to highest on the vertical axis, included:

1. Basic Research;
2. Industry Applications;
3. Military Applications; and
4. Maritime Applications.

The four categories of ***Literature Type***, from lowest to highest on the horizontal axis, included:

1. Conceptual;
2. Laboratory Experiment;

3. Field Evaluation; and

4. Literature Review.

Once relevant titles were categorized they were further reviewed and assessed using criteria given in ***Table 2*** (*Criteria for the Critical Analysis – Initial Assessment*) below.

Table 2. Criteria for the Critical Analysis – Initial Assessment

REFERENCE: _____ **CATEGORY:** _____

CRITICAL ANALYSIS CRITERIA	SCALE STRUCTURE
1. Topic's relationship to the main topic of interest to the project (see Section 1.2 above).	1. Indirectly related 2. Directly related 3. Exact match
2. Level of detail provided regarding the methodology and the data collection techniques.	1. Less than adequate 2. Adequate 3. More than adequate
3. Adequacy of research design to answer research questions.	1. Less than adequate 2. Adequate 3. More than adequate
4. Adequacy of the chosen methodology to obtain reliable data.	1. Less than adequate 2. Adequate 3. More than adequate
5. Relevance of the methodology to Maritime C4I environments (validity).	1. Indirectly related 2. Directly related 3. Exact match
6. Reliability of the results based on sample size, data collection techniques, objectivity of data, etc.	1. Low 2. Medium 3. High
7. Level of contribution to the body of knowledge on operator performance using multiple displays.	1. Low 2. Medium 3. High

This table was created to meet one of the project goals, which was to provide an indication of the quality of the literature. Each literature was assessed for each criterion, and the totals for each literature were tallied and entered into a summary table, and assigned a ranking as shown in ***Table 3*** (*Literature Ranking*) below.

Table 3. Literature Ranking

	CRITICAL ANALYSIS CRITERIA							
LITERATURE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**TOTAL**
Literature 1								
Literature 2								
Literature 3								
.								
.								
.								

The literature was then arranged by rank within each category, and the highest-ranking literature was profiled and considered for a detailed review.

2.3 Detailed Literature Review

Once the literature was organized into its respective category of type, 7 of the 100 documents, reports, papers and/or articles were selected for a more detailed review. This selection was based on a review of the abstracts of the literature listed in the ***Bibliography***.

Once the detailed literature review was completed, an assessment of the breadth, depth and quality of the literature was developed, along with recommendations for areas of further research in the future. These final assessments were integrated into this final report.

3. Summary of Findings and Discussion

Using the keywords and literature sources outlined in Section 2.1 a total of 152 documents, reports, papers and/or articles, of which 100 of the most relevant literature have been chosen and categorized using a category matrix, to produce the literature distribution illustrated in ***Table 4*** (*Literature Categorization Results*) below.

Table 4. Literature Categorization Results

		LITERATURE TYPE			
		CONCEPT	**LAB**	**FIELD**	**REVIEW**
DOMAIN RELEVANCE	**MARITIME**	2	8	1	2
	MILITARY	4	8	2	12
	INDUSTRY	2	11	1	4
	BASIC	9	24	1	9

Note that the numbers in each cell indicate the number of documents in the project assigned to that domain relevance and literature type.

3.1 Literature Categorization Results

The relevant literature was categorized in terms of domain as shown in ***Figure 2*** (*Literature by Domain*) below.

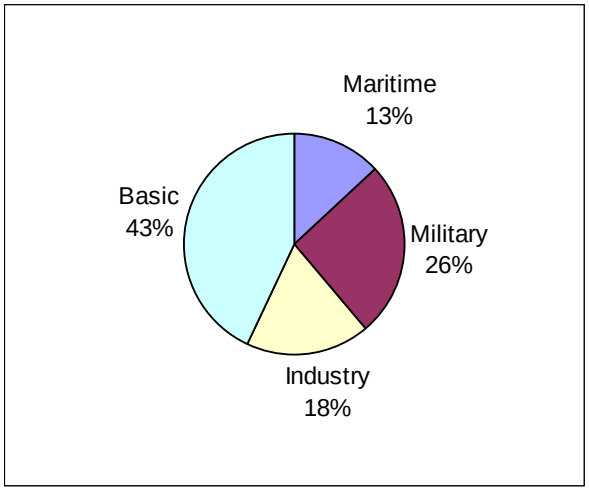

Figure 2. Literature by Domain

The above figure clearly demonstrates that there is a substantial base of literature from Basic (43%) research, which is directed mostly at visual displays. There is also a substantial base of literature from Military (26%) applications, which is directed mostly at aviation cockpit displays. Not surprisingly, the number of Military (26%) work is double the literature related directly to Maritime (13%) work. But there is surprisingly less literature from Industrial (18%) domains, such as transportation.

The relevant literature was also categorized in terms of type as shown in ***Figure 3*** (*Literature by Type*) below.

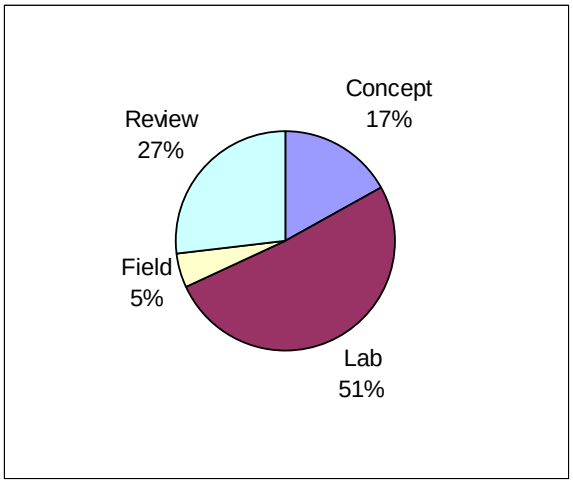

Figure 3. Literature by Type

As illustrated above, more than half of the literature identified is in the category of Laboratory (51%) experiment. This reflects the lack of maturity of the domain, in that Concepts (17%) have been generated and are still being thoroughly tested. Even further, there is a noticeable lack of Field (5%) evaluations supporting this conclusion.

Another reason for the heavy weighting of literature in the area of tested concepts is that the area of operator performance using multiple displays is very much a technology-enabled field. As new technologies are developed in an extremely fast pace, possible forms of display support also change. The available technologies for operator performance support have been developing very rapidly, and with such technological expansion, there are many rewards in the publication and commercialization for testing exciting concepts. This pattern is seen to a large extent in the human-computer interaction literature and the basic research category. However, that pattern continues in the military and industrial categories, with a heavy concentration on evaluation in the laboratory and a slower movement towards new concepts or field evaluations.

3.2 Literature Ranking Results

Of the literature identified in the survey, and summarized in Section 3.1, a number of documents were selected for a more detailed review. This list was developed based on a review of the abstracts of the literature listed in the ***Bibliography***. Unfortunately, the limited budget for the project provided time for a review of only 7 best-ranked documents shown in ***Table 4*** (*Literature Ranking Results*) below.

Table 4. Literature Ranking Results

LITERATURE	TOTAL
DiVita, J.C., Obermayer, R., Nugent, W., and Linville, J.M. (2004)	17
Durlach, P.J. (2004)	17
Hale, K.S. and Stanney, K.M. (2003)	17
Samman, S.N., Stanney, K.M. and Sims, V.K.	16
Stanney, K.M., Samman, S.N., Reeves, L., Hale, K.S., Buff, W….(2004)	16
St. John, M. Manes, D.I., Oonk, H.M., and Ko, H. (1999)	16
Wickens, C.D., Vincow, M.A., Schopper, A.W., and Lincoln, J.E. (1997)	16

The next section presents a short summary of the literature and brief comments on how multiple displays apply to Maritime C4I.

3.3 Literature Reviewed in Detail

DiVita, J.C., Obermayer, R., Nugent, W., and Linville, J.M. (2004). *Verification of the Change Blindness Phenomenon While Managing Critical Events on a Combat Information Display.* Change blindness occurs when humans are unable to detect significant changes in objects and scenes after their attention is momentarily diverted. Because change blindness is relevant in many applied settings, the study investigated the phenomenon in the context of tasks performed by naval command and control system personnel. Operators of such systems are often heavily loaded with concurrent visual search, situation assessment, voice communications, and control display manipulation tasks at large, physically dispersed tactical situation displays. As the operators' attention shifts from one display to another, it creates an opportunity for changes to occur on unattended screens with potentially negative consequences. The results show that on a display containing 8 objects of interest, considerable change blindness was demonstrated in that participants required 2 or more selections to correctly identify a changed object on nearly 1/3 of the test trials. Further, operator performance on 15% of the trials was equivalent to randomly guessing with replacement after making 3 incorrect selections. This research underscores the need for developing effective countermeasures to the change blindness phenomenon. Actual or potential uses of this research include interface design of computer workstations for military applications.

Durlach, P.J. (2004). *Change Blindness and Its Implications for Complex Monitoring and Control Systems Design and Operator Training.* Recent research on change detection suggests that people often fail to notice changes in visual displays when they occur at the same time as various forms of visual transients, including eye blinks, screen flashes, and scene relocation. Distractions that draw the observer's attention away from the location of the change especially lead to detection failure. As process monitoring and control systems rely

on humans interacting with complex visual displays, there is a possibility that important changes in visually presented information will be missed if the changes occur coincident with a visual transient or distraction. The purpose of this article was to review research on so called "change blindness" and discuss its implications for the design of visual interfaces for complex monitoring and control systems. The major implication is that systems should provide users with dedicated change-detection tools, instead of leaving change detection to the vagaries of human memorial and attentional processes. Possible training solutions for reducing vulnerability to change-detection failure are also discussed.

Hale, K.S. and Stanney, K.M. (2003). *Deriving Haptic Design Guidelines from Human Physiological, Psychophysical, and Neurological Foundations.* In order to realize successful integration of haptic interactions into multimodal systems, the sensory, perceptual and cognitive abilities and limitations of users must be examined, and accounted for in the design of haptic systems. To date, many interactive systems have focused on visual cues, and to a lesser extent, audio cues, for presenting information to users concerning their surroundings and interactions with objects. The haptic sense offers another independent sensory channel that can be processed in the brain to further enhance the user's experience in a multimodal environment. By adding in haptic feedback, realism of the system should be enhanced through more natural interaction with objects and environmental surroundings. This survey paper begins with a review of physiological and psychophysical aspects of human cutaneous and kinesthetic senses. From there, issues of incorporating haptics interaction into a visual display are discussed. Based on an exhaustive literature review, the paper offers many haptics design guidelines to aid developers of multimodal interactive systems.

Samman, S.N., Stanney, K.M. and Sims, V.K. *Think Multimodal to Maximize Information management Capacity.* New human-computer interaction paradigms are being developed that transform user interaction from a primarily visual experience to one that uses multiple senses. While research has advanced in the development of technological breakthroughs, relatively little research has examined the cognitive factors of the user during multimodal multitasking operations. Thus, designers may face problems when creating interfaces that allow operators to process the optimal amount of data. It is herein proposed that more effective multimodal interaction can be accomplished by creating multimodal display systems that are expressly designed to maximize user information processing across the sensory systems. Rather than information overload, the benefits of such systematically designed multimodal interaction should be greater information assimilation, retention, and recall. A theoretically derived multimodal interaction framework is proposed that leverages multiple sensory systems to maximize working memory (WM) throughput. Multiple resource theory (MRT) suggests that enhancements in human information management capacity may be realized via multimodal interaction. The current study proposes an expansion of the traditional bi-modal (verbal, visual/spatial) model of WM to a multimodal WM system, which includes verbal, visual, spatial, kinesthetic, tactile, and tonal component subsystems. Single modality capacity was measured for each proposed subsystem. In addition, multimodal capacity was calculated for combined modalities. Results demonstrated that multimodal WM capacity surpasses that of single modality capacity. Most notably, multimodal WM capacity averaged more than three times the traditional capacity limitation of unidimensional WM. Applications for the multimodal WM framework are relevant when designing multimodal systems for multitasking environments such as those conduced by air traffic controllers, emergency room physicians, and stock brokers.

Stanney, K.M., Samman, S.N., Reeves, L., Hale, K.S., Buff, W., Bowers, C., Goldiez, B, Nicholson, D., and Lackey, S. (2004). *A Paradigm Shift in Interactive Computing: Deriving Multimodal Design Principles from Behavioral and Neurological Foundations.* As technology advances, systems are increasingly able to provide more information than a human operator can process accurately. Thus, a challenge for designers is to create interfaces that allow operators to process the optimal amount of data. It is herein proposed that this may be accomplished by creating multimodal display systems that augment or switch modalities to maximize user information processing. Such a system would ultimately be informed by a user's neurophysiological state. As a first step toward that goal, relevant literature is reviewed and a set of preliminary design guidelines for multimodal information systems is suggested.

St. John, M. Manes, D.I., Oonk, H.M., and Ko, H. (1999). *Workspace Control Diagrams and Head-Mounted Displays as Alternatives to Multiple Monitors in Information-Rich Environments.* In environments such as Navy command and control, supervision and multi-tasking are often hindered by a shortage of screen space. An obvious solution is to use more or larger monitors. An inexpensive and practical alternative is to use an interface that allows rapid switching between workspaces (screens of information), providing, in effect, a large virtual desktop. One potentially effective switching interface is a workspace control diagram: a meaningful arrangement of buttons, each of which provides access to and information for a particular workspace. In the first experiment, participants best performed a task that required frequent navigation among workspaces using two real monitors but were nearly as proficient when using one monitor with a workspace control diagram operated by hot keys. In the second experiment, participants performed concurrent tracking and monitoring tasks about equally using four monitors with all workspaces visible and using two monitors with a workspace control diagram. Additionally, the authors discuss the potential of a much more radical workstation design alternative: head-mounted displays.

Wickens, C.D., Vincow, M.A., Schopper, A.W., and Lincoln, J.E. (1997). *Computational Models of Human Performance in the Design and Layout of Controls and Displays.* This literature describes both conceptual and empirically derived models pertaining to the layout and grouping of information within display panels and display screens. Several of the models reviewed are also applicable to the spatial organization of controls and displays. Principles relating to centrality of location, symmetry, clutter, frequency of use, sequence of use, relative importance, and relatedness are considered. The models are organized into three areas: (a) physical arrangements of the information to be displayed emphasizing issues such as overall and local screen density, grouping, and alignment, (b) interrelationships derived from content and task-related factors and information processing considerations, and (c) more comprehensive conceptual and software-based engineering models derived from groupings, density, and task-related consideration; relative importance of various components and information groups; and relative distance and location.

4. Conclusions and Recommendations

A survey of the literature related to operator performance using multiple displays has been completed in order to provide feedback on the domain, type and quality of the literature and to recommend areas of future research. The type of literature identified indicated that there is more relevant literature in the military than the maritime domain. There is also a substantial base of literature from basic research, which is directed mostly at visual displays. This literature base, however, does not have much depth. Much of the literature is at the experimental phase of development. This reflects the lack of maturity of the domain, in that less new ideas have been generated than have been tested.

In cases where actual evaluations of multiple display technologies have been conducted there are a number of concerns with the quality of research, particularly as a result of unrepresentative subject groups and tasks, inappropriate measures, and poor interface design of displays.

Human factors research on complex processes, both their control and their fault management and diagnosis, remains an immature domain. Many of the recommendations concerning displays translate directly from the general practice of good human factors, and this approach has been implemented with some degree of success. Yet it is equally clear that great improvements are possible by combining theories of cognitive psychology with increasingly available computer and display technology. This area of cognitive engineering is one in which relatively little engineering psychology research has been conducted to assess the utility of the recommendations made by such researchers as Wickens, Stanney and St. John. The potential payoffs of this research appear to be quite high, in light of the fact that systems are evolving toward greater complexity with increasing levels of automation.

In order to extend the literature, in a manner that would generate valid guidance for future operator performance using multiple displays in the maritime environment, it is recommended that a research and development program be conducted, as follows:

4. Extend the literature review on operator performance using multiple displays;

5. Conduct maritime multiple display experiments; and

6. Coordinate and consolidate multiple display research.

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Annex A – Literature Categorization Matrix

		LITERATURE TYPE			
		CONCEPT	**LAB**	**FIELD**	**REVIEW**
DOMAIN RELEVANCE	**MARITIME**	1. Meyer, Sandhu...(2002) 2. Nugent, White (2000)	1. DiVita, Nugent (2000) 2. Hutchins (1997) 3. Nugent (1994) 4. Nugent (1996) 5. Nugent, Broyles (1992) 6. St. John, Manes...(2004) 7. St. John, Smallman...(2005) 8. Van Orden, Nugent...(1999)	1. DiVita, Obermayer...(2004)	1. Burns, Greenley...(2002) 2. Layman, Weatherly (2004)
	MILITARY	1. Hopper (1998) 2. Hopper (1999) 3. Hopper (2000) 4. Hopper, 1000X… (2000)	1. Durlach (2004) 2. Durlach, Carnahan...(2004) 3. Kuperman, Brickner...(1999) 4. Lickteig, Novice...(2004) 5. Nelson, Bolia...(1999) 6. Snow, French...(2003) 7. Tannen, Nelson...(2000) 8. Yeh, Merlo...(2003)	1. Banks, Wickens (1997) 2. Glumm, Branscome...(1999)	1. Arrabito (2000) 2. Desjardins, Hopper (1999) 3. Durlach, CB (2004) 4. Fullenkamp (2004) 5. Hutchins (2001) 6. Hutchins, Kemple...(1997) 7. Kocian (1990) 8. Lickteig, A Focus...(2003) 9. Lickteig, Future...(2004) 10. Lickteig, Human...(2003) 11. Lickteig, Measurement...(2004) 12. Naikar (1998)
	INDUSTRY	1. Mackinlay, Heer (2004) 2. Wickens, Display...(2005)	1. Bud, Stearns...(1998) 2. Donderi, McFadden (2003) 3. Jones, Samman... 4. Lanzilotta, Sheridan (2005) III 5. Marinakos, Sheridan...(2005) 6. Meyer, Sandhu...(2002) 7. Muthard, Wickens (2004) 8. Muthard, Wickens (2005) 9. Wickens, Alexander...(2004) 10. Wickens, Dixon...(2003) 11. Wickens, Goh...(2003)	1. Grudin (2001)	1. Kaber, Riley...(2001) 2. Mandal (2003) 3. Mejdal, McCauley...(2001) 4. Post, Task (2001)

	LITERATURE TYPE			
	CONCEPT	**LAB**	**FIELD**	**REVIEW**
BASIC	1. Bisantz, Pritchett (2003) 2. Hornof (2004) 3. Lee, Vickers (1998) 4. Pattison, Vernik...(2001) 5. Slay, Thomas... 6. Smallman…(2005) 7. Vicente (2003) 8. Vogels (2004) 9. Wee, Chua (2004)	1. Akeley, Watt...(2004) 2. Anderson (2005) 3. Bera, Robinson (2004) 4. Boot, Kramer... 5. Cole, Kentridge (2004) 6. Dessing, Peper...(2004) 7. DiVita, Rock (1997) 8. Harris, Morris (2004) 9. Hinckley, Ramos...(2004) 10. Hutchings, Smith...(2004) 11. Konrad, Kramer...(1996) 12. Mandryk, Rodgers...(2005) 13. Murata (2004) 14. Murray (1994) 15. Murray (1995) 16. Nikolic, Orr...(2004) 17. Oliva, Wolfe...(2004) 18. Olivers (2004) 19. Samman, Stanney... 20. Singer, Ehrlich...(1995) 21. St. John, Harris...(1997) 22. St. John, Manes (2002) 23. St. John, Manes...(1999) 24. Vogels (2004)	1. Hutchings, Stasko (2004)	1. Burdea (2003) 2. Chapanis (1996) 3. Hale, Stanney (2003) 4. Hettinger, Haas (2003) 5. Sheridan (2002) 6. Stanney (2002) 7. Stanney, Samman...(2004) 8. Wickens, Attentional…(2005) 9. Wickens, Vincow…(1997)

Annex B – Literature Ranking

	CRITICAL ANALYSIS CRITERIA							
LITERATURE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**TOTAL**
Akeley, Watt...(2004)	1	2	2	2	1	2	2	12
Anderson (2005)	1	2	2	2	1	2	2	12
Arrabito (2000)	2	2	2	2	2	2	3	15
Banks, Wickens (1997)	2	2	2	2	2	2	3	15
Bera, Robinson (2004)	1	2	2	2	1	2	2	12
Bisantz, Pritchett (2003)	1	2	2	2	1	2	2	12
Boot, Kramer...	1	2	2	2	1	2	2	12
Bud, Stearns...(1998)	1	2	2	2	1	2	2	12
Burdea (2003)	1	2	2	2	1	2	2	12
Burns, Greenley...(2002)	2	2	2	2	2	2	3	15
Chapanis (1996)	1	2	2	2	1	2	2	12
Cole, Kentridge (2004)	1	2	2	2	1	2	2	12
Desjardins, Hopper (1999)	1	2	2	2	1	2	1	11
Dessing, Peper...(2004)	1	2	2	2	1	2	1	11
DiVita, Nugent (2000)	2	2	2	2	2	2	3	15
DiVita, Obermayer...(2004)	**3**	**2**	**2**	**2**	**3**	**2**	**3**	**17**
DiVita, Rock (1997)	1	2	2	2	1	2	1	11
Donderi, McFadden (2003)	1	2	2	2	1	2	2	12
Durlach (2004)	1	2	2	2	1	2	2	12
Durlach, Carnahan...(2004)	1	2	2	2	1	2	1	11
Durlach, CB (2004)	**3**	**2**	**2**	**2**	**3**	**2**	**3**	**17**
Fullenkamp (2004)	1	2	2	2	1	2	1	11
Glumm, Branscome...(1999)	1	2	2	2	1	2	1	11
Grudin (2001)	1	2	2	2	1	2	1	11
Hale, Stanney (2003)	**3**	**2**	**2**	**2**	**3**	**2**	**3**	**17**
Harris, Morris (2004)	1	2	2	2	1	2	1	11
Hettinger, Haas (2003)	1	2	2	2	1	2	2	12
Hinckley, Ramos...(2004)	1	2	2	2	1	2	2	12
Hopper (1998)	1	2	2	2	1	2	2	12
Hopper (1999)	1	2	2	2	1	2	2	12
Hopper (2000)	1	2	2	2	1	2	2	12
Hopper, 1000X... (2000)	1	2	2	2	1	2	2	12
Hornof (2004)	2	2	2	2	2	2	3	15
Hutchings, Smith...(2004)	2	2	2	2	2	2	3	15
Hutchings, Stasko (2004)	2	2	2	2	1	1	2	12
Hutchins (1997)	1	2	2	2	1	2	2	12
Hutchins (2001)	1	2	2	2	1	2	2	12
Hutchins, Kemple...(1997)	1	2	2	2	1	2	2	12
Jones, Samman...	2	2	2	2	2	2	3	15
Kaber, Riley...(2001)	1	2	2	2	1	2	2	12
Kocian (1990)	1	2	2	2	1	2	2	12
Konrad, Kramer...(1996)	1	2	2	2	1	2	2	12

	CRITICAL ANALYSIS CRITERIA							
LITERATURE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**TOTAL**
Kuperman, Brickner...(1999)	1	2	2	2	1	2	2	12
Lanzilotta, Sheridan (2005) III	1	2	2	2	1	2	1	11
Layman, Weatherly (2004)	2	2	2	2	3	2	2	15
Lee, Vickers (1998)	1	2	2	2	1	2	2	12
Lickteig, A Focus...(2003)	1	2	2	2	2	2	2	13
Lickteig, Future...(2004)	1	2	2	2	2	2	2	13
Lickteig, Human...(2003)	1	2	2	2	2	2	2	13
Lickteig, Measurement...(2004)	1	2	2	2	2	2	2	13
Lickteig, Novice...(2004)	1	2	2	2	2	2	2	13
Mackinlay, Heer (2004)	1	2	2	2	2	2	2	13
Mandal (2003)	1	2	2	2	1	2	1	11
Mandryk, Rodgers...(2005)	1	2	2	2	2	2	2	13
Marinakos, Sheridan...(2005)	1	2	2	2	1	2	2	12
Mejdal, McCauley...(2001)	2	2	2	2	1	2	1	12
Meyer, Sandhu...(2002)	1	2	2	2	1	2	1	11
Meyer, Sandhu...(2002)	1	2	2	2	2	2	1	12
Murata (2004)	1	2	2	2	1	2	2	12
Murray (1994)	2	2	2	2	3	2	2	15
Murray (1995)	2	2	2	2	3	2	2	15
Muthard, Wickens (2004)	1	2	2	2	2	2	2	13
Muthard, Wickens (2005)	1	2	2	2	2	2	2	13
Naikar (1998)	2	2	2	2	3	2	2	15
Nelson, Bolia...(1999)	2	2	2	2	2	2	3	15
Nikolic, Orr...(2004)	1	2	2	2	1	2	2	12
Nugent (1994)	1	2	2	2	2	2	2	13
Nugent (1996)	1	2	2	2	2	2	2	13
Nugent, Broyles (1992)	1	2	2	2	2	2	2	13
Nugent, White (2000)	1	2	2	2	2	2	2	13
Oliva, Wolfe...(2004)	1	2	2	2	1	2	1	11
Olivers (2004)	1	2	2	2	2	2	2	13
Pattison, Vernik...(2001)	1	2	2	2	1	2	1	11
Post, Task (2001)	1	2	2	2	2	2	2	13
Samman, Stanney...	**3**	**2**	**2**	**2**	**3**	**2**	**2**	**16**
Sheridan (2002)	1	2	2	2	1	2	1	11
Singer, Ehrlich...(1995)	1	2	2	2	2	2	1	12
Slay, Thomas...	1	2	2	2	1	2	1	11
Smallman...(2005)	1	2	2	2	2	2	1	12
Snow, French...(2003)	1	2	2	2	1	2	2	12
Stanney (2002)	2	2	2	2	2	2	2	14
Stanney, Samman...(2004)	**2**	**2**	**2**	**2**	**3**	**2**	**3**	**16**
St. John, Harris...(1997)	2	2	2	2	2	2	2	14
St. John, Manes (2002)	1	2	2	2	1	2	2	12
St. John, Manes...(1999)	**2**	**2**	**2**	**2**	**3**	**2**	**3**	**16**
St. John, Manes...(2004)	1	2	2	2	3	2	2	14

	CRITICAL ANALYSIS CRITERIA							
LITERATURE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**TOTAL**
St. John, Smallman...(2005)	1	2	2	2	3	2	2	14
Tannen, Nelson...(2000)	2	2	2	2	3	2	2	15
Van Orden, Nugent...(1999)	1	2	2	2	2	2	2	13
Vicente (2003)	1	2	2	2	2	2	2	13
Vogels (2004)	1	2	2	2	1	2	2	12
Wee, Chua (2004)	1	2	2	2	1	2	2	12
Wickens, Attentional...(2005)	2	2	2	2	2	2	2	14
Wickens, Display...(2005)	2	2	2	2	2	2	2	14
Wickens, Alexander...(2004)	1	2	2	2	2	2	2	13
Wickens, Dixon...(2003)	2	2	2	2	2	2	2	14
Wickens, Goh...(2003)	2	2	2	2	2	2	2	14
Wickens, Vincow…(1997)	**3**	**2**	**2**	**2**	**2**	**2**	**3**	**16**
Yeh, Merlo...(2003)	1	2	2	2	2	2	1	12

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List of Symbols / Abbreviations / Acronyms / Initialisms

ACE	Association of Canadian Ergonomists
ACM	Association of Computing Machinery
AECL	Atomic Energy of Canada Limited
C2	Command and Control
C3	Command, Control and Communication
C4	Command, Control, Communications and Computer
C4I	Command, Control, Communications, Computer and Intelligence
CISTI	Canada Institute for Scientific and Technical Information
CSERIAC	Crew System Ergonomics Information Analysis Center
CTA	Cognitive Task Analysis
DDSM	Directory of Design Support Methods
DND	Department of National Defence
DoD	U.S. Department of Defense
DRDC	Defence Research and Development Canada
DSTO	Defence Science and Technology Organization
DTIC	Defense Technical Information Center
EEVL	Edinburgh Engineering Virtual Library
EPRI	Electronic Power Research Institute
FOV	Field of View
HCI	Human-Computer Interaction
HFES	Human Factors and Ergonomics Society
HSIAC	Human Systems Information Analysis Center

IAC	Information Analysis Centers
LEA	Lawrence Erlbaum Associates
MRT	Multiple Resource Theory
MSIS	Man-Systems Integration Standards
NASA	National Aeronautics and Space Administration
NRC	U.S. Nuclear Regulatory Commission
NRCC	National Research Council Canada
OPSAD	Operator Performance and Safety Division
PWGSC	Public Works and Government Services Canada
RSPA	Research and Special Programs Administration
SPAWAR	Space and Naval Warfare Systems Command
WM	Working Memory

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1. ORIGINATOR (The name and address of the organization preparing the document, Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's document, or tasking agency, are entered in section 8.)

Publishing: DRDC Atlantic

Performing: Valcom Consulting Group Inc., 1969 Upper Water Street, Purdy's Wharf, Tower 2, Suite 2200,Halifax , NS, B3J 3R7

Monitoring:

Contracting: Valcom Consulting Group Inc., 1969 Upper Water Street, Purdy's Wharf, Tower 2, Suite 2200,Halifax , NS, B3J 3R7

2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

Literature survey on operator performance using multiple displays (U)
Étude documentaire sur le rendement des opérateurs travaillant avec des affichages multiples

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Vincenzo Delle Donne

5. DATE OF PUBLICATION (Month and year of publication of document.)

March 2006

6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)

58

6b. NO. OF REFS (Total cited in document.)

151

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical document, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (The names of the department project office or laboratory sponsoring the research and development − include address.)

Sponsoring: DRDC Atlantic

Tasking: DRDC Atlantic

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant under which the document was written. Please specify whether project or grant.)

16kh03

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document)

DRDC Atlantic CR 2005−209

10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

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(U) A survey has been completed to investigate literature in the area of operator performance using multiple displays, in order to support a variety of projects in the Maritime Command, Control, Communications, Computer and Intelligence (C4I) environment at Defence Research and Development Canada (DRDC) Atlantic. Using a defined set of keywords and literature sources, various documents, reports, papers and articles were found, of which 100 were assessed according to a set of criteria that identified those that were more useful for adaptation to the present project's goals and objectives. Of the literature identified in the survey, 7 were reviewed in detail and summarized.

(U) Une étude des documents portant sur le rendement des opérateurs qui travaillent avec des affichages multiples a été menée dans le but d'appuyer une variété de projets de commandement, de contrôle, de communications, d'informatique et de renseignement (C3IR) dans le milieu maritime à Recherche et développement pour la défense Canada − Atlantique (RDDC). À l'aide d'un ensemble défini de mots clés et de sources documentaires, nous avons trouvé divers documents, rapports, journaux et articles. Nous avons évalué 100 de ces documents en fonction d'un ensemble de critères qui ont permis de cerner ceux qui s'adapteraient le mieux aux objectifs et aux buts du projet en cours. À partir des documents retenus, nous en avons examiné 7 en détail et les avons résumés.

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(U) multiple monitors, human performance, attention, maritime, command and control

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